Ocean color instrument intercomparisons and cross-calibrations by the SIMBIOS Project (1999-2000)

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ABSTRACT

The NASA Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) Project has a worldwide, ongoing ocean color data collection program, as well as an operational data processing and analysis capability. SIMBIOS data collection takes place via the SIMBIOS Science Team and the NASA Aerosol Robotic Network (AERONET). In addition, SIMBIOS has a calibration and product validation component. The primary purpose of these calibration and product validation activities are to (1) reduce measurement error by identifying and characterizing true error sources such as real changes in the satellite sensor or problems in the atmospheric correction algorithm, in order to differentiate these errors from natural variability in the marine light field; and (2) evaluate the various bio-optical algorithms being used by different ocean color missions. For each sensor, the SIMBIOS Project reviews the sensor design and processing algorithms being used by the particular ocean color project, compares the algorithms with alternative methods when possible, and provides the results to the appropriate project office.

Keywords: SeaWiFS, MOS, OCTS, POLDER, sensor intercomparison, SIMBIOS

1. INTRODUCTION

Between 1996 and 2002, nine major international ocean-color satellite missions capable of providing routine global data will be in orbit. The SIMBIOS Program goal is to assist the international ocean color community in developing a multi-year time-series of calibrated radiances which transcends the spatial and temporal boundaries of individual missions. These ocean color missions are highly complementary and congruent in many important respects. However, they also exhibit significant differences in technical approach which have implications for calibration, navigation, atmospheric correction, bio-optical algorithm development, and data products. From the user's perspective, it is an open question as to what extent the data will be compatible. To answer this question, the differences among missions must be resolved or explained. One important goal of the SIMBIOS Program is to assist the international ocean color community in developing a multi-year time-series of calibrated radiances which transcends the spatial and temporal boundaries of individual missions.

The specific objectives of the SIMBIOS Program are: (1) to quantify the relative accuracies of the ocean color products from each mission, (2) to work with each project to improve the level of confidence and compatibility among these products, and (3) to develop methodologies for generating merged level-3 products. SIMBIOS has identified the primary instruments to be used for developing global data sets. These instruments are SeaWiFS, OCTS, POLDER (ADEOS-I and II), MODIS (Terra and Aqua), MISR, MERIS, and GLI. The products from other missions (e.g., OCI and the two MOS sensors) will be tracked and evaluated, but are not considered as key data sources for a combined global data set.

The organizational approach includes the SIMBIOS Project Office[1,2] located at Goddard Space Flight Center (GSFC) (http://simbios.gsfc.nasa.gov) and the SIMBIOS Science Team. The Science Team is selected through NASA Research Announcements (NRA's) 1996 and 1999. The Project funds numerous US investigators and collaborates with several international investigators, space agencies (e.g., NASDA, CNES) and international organizations (e.g., IOCCG, JRC). US investigators under contract provide *in situ* atmospheric and bio-optical data sets, and develop algorithms and methodologies for data merger schemes. The locations of specific SIMBIOS team investigations are shown in Figures 1and 2.

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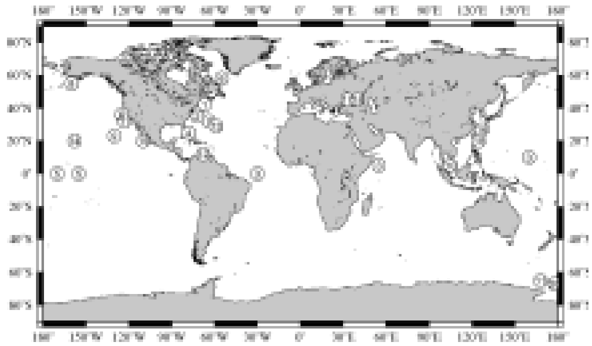

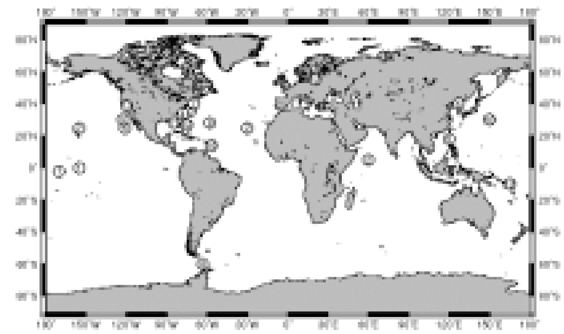

Figure 1. Global distribution of the NRA-96 selected SIMBIOS studies. United States (field): (1) Balch; (2) Brown/Brock; (3) Capone/Carpenter/Subraniam; (4) Carder and Green; (5) Chavez; (6) Cota; (7) Dickey; (8) Eslinger; (9) Frouin; (10) Miller; (11) Mitchell and Green; (12) Müller-Karger; (13) Siegel; (14) Porter (15) Zaneveld and Mueller. United States (theoretical): Flatau; Siegel and Stamnes. International: (16) He; (17) Korotaev; (18) Kopelevich; and (19) Li.

Figure 2. Global distribution of the NRA-99 selected SIMBIOS studies. United States (field): (1) Chavez; (2) Frouin; (3) Gao; (4) Harding; (5) Miller; (6) Mitchell; (7) Morrison; (8) Nelson; (9) Siegel; (10) Spinhirne; (11) Stumpf; (12) Subramaniam; (13) Zalewski. United States (theoretical): Gregg; Hooker; Maritorena; Mueller; Trees and Wang. International: Bohm; Zibordi; Fougnie; Deschamps; Antoine; Kopelevich; Ishizaka; Fukushima; Chen; Li; He and Tang.

The SIMBIOS Project Office[1,2], co-located with the SeaWiFS Project Office, provides support and coordination for the SIMBIOS Program such as administration, project documentation, and interagency and international coordination. It also incorporates aspects of instrument calibration, measurement protocol experiments, round robins, algorithm development and evaluation, product merging, and data processing (Figure 3).

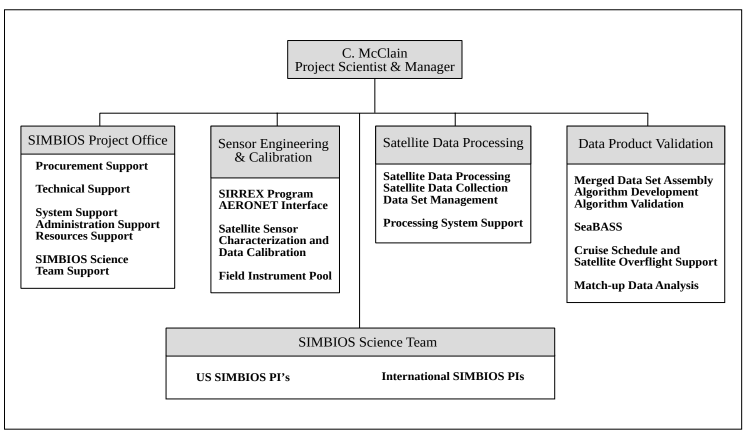

Figure 3. SIMBIOS Project Organization Chart

2. METHODOLOGY AND DATA

Satellite instruments use a variety of onboard measurements, including lamps, solar diffusers with ratioing radiometers, and lunar measurements to monitor changes in sensor operation on orbit[3]. These onboard methods vary from instrument to instrument, and as such, they do not provide a method for intercalibrating the ensemble of ocean color sensors. However, there are vicarious calibration test sites, both instrumented[4] and uninstrumented[5], which complement the on-board measurements. For SeaWiFS[6] and MODIS the Marine Optical Buoy (MOBY)[7] provides the principal instrumented test site for vicarious calibration measurements[8], and the Sargasso Sea[9] and the Bermuda Bio-optical Program (BBOP) time series provides useful uninstrumented test sites.

Recently, at the IOCCG Hobart meeting (February 2000), the members restated that to be effective, satellite/sensor providers must have a common strategy[10]. In the near future, an international group of investigators will compare various atmospheric correction algorithms using simulated data. The chair of this activity will be Dr. Wang, a member of the SIMBIOS Science Team (NRA-99). The SIMBIOS Project expects that the comparison of available atmospheric correction algorithms (i.e., CZCS, OCTS, SeaWiFS, POLDER, GLI, MERIS and MODIS) on generated data sets will provide valuable lessons in the evaluation of, and comparisons between, these algorithms.

The application of identical atmospheric methods to different sensors helps to separate algorithm problems from sensor problems, leading to more robust atmospheric correction algorithms. Specifically, the use of multi-view instruments like POLDER and MISR can be used to test the consistency of the algorithm as a function of satellite viewing angle. Also, instruments with similar center wavelengths but differing bands can provide data on effects of out-of-band response. Presently, the SIMBIOS Project and SeaWiFS Program have available for use the Gordon and Wang[11,14] atmospheric correction algorithm which is being incrementally improved. The SIMBIOS research program (i.e., NRA-99), through strong international partnering, will assist the satellite/sensor providers in determining how best to accomplish data merger.

2.1. Vicarious calibration

The primary purpose of SIMBIOS calibration activity is to reduce measurement error by identifying and characterizing error sources such as real changes in satellite sensors and problems in the atmospheric correction algorithms, in order to differentiate them from natural variability in the marine light field. For each sensor, the SIMBIOS Project reviews the sensor design and processing algorithms being used by the particular ocean color project, compares the algorithms with alternative methods when possible, and provides the results to the appropriate project office.

Presently, SIMBIOS uses a combination of vicarious (*in situ*-based observation) test sites as a means of comparing ocean color satellite instruments. Using the vicarious calibration approach, results retrieved from different sensors can be meaningfully compared and possibly merged. More importantly, one can recalibrate satellite sensors using *in situ* ocean and atmospheric optical property measurements with the same procedure.

The present calibration strategy is to focus on regions where the optical properties of the marine atmosphere and ocean are well understood and homogeneous, i.e., where the errors in the atmospheric correction and the *in situ* optical measurements are expected to be minimal. The MOBY Project[9] supports the validation of ocean color data that is collected by SeaWiFS, and MODIS (see http://ltpwww.gsfc.nasa.gov/MODIS/MODIS.html). MOBY is deployed off Lanai (Hawaii) and provides water-leaving radiances at subnanometer resolution from 340-950 nm. These radiances can be convolved with the spectral responses of the ocean color bands of satellite sensors to give band-averaged radiances for the instruments. This is done, for example, for the vicarious calibration of the SeaWiFS instrument[12]. Since the greatest portion of the radiances measured by ocean color sensors at the top-of-the-atmosphere comes from the atmosphere itself, the vicarious calibration of these instruments at MOBY is made to the "instrument/atmospheric correction system"[13]. For the atmospheric correction algorithm, contributions to the top-of-the-atmosphere radiance, such as the solar flux scattered upwards by air molecules, can be calculated exactly. However, the calculation of the upwelling radiance from atmospheric aerosols requires knowledge of both the aerosol type and its amount. MOBY measurements are not used as part of the vicarious calibration of the near infrared bands used to determine atmospheric aerosols by ocean color satellite instruments, since the clear, low-chlorophyll ocean waters near MOBY contribute water-leaving radiances that are negligible. However, the region around the MOBY site can be used for vicarious calibration in the near infrared[12] (relative to 865 nm, only, for SeaWiFS). MOBY collects and transmits data that are processed and made available to the SeaWiFS Project Office on a daily basis. MOBY has been successfully used for SeaWiFS[8], OCTS, POLDER and MOS calibration[1,2,15].

The present approach used by the SIMBIOS Project Office (Table 1) is to develop a Level-1b to Level-2 software package (MSl12) which is capable of processing data from multiple ocean color sensors using the standard SeaWiFS atmospheric correction algorithms of Gordon and Wang[11,14]. The integration of a new sensor into MSl12 involves the development of a set of input functions and derivation of band-pass specific quantities such as Rayleigh scattering tables and Rayleigh-aerosol transmittance tables. Once the processing capability has been established, the vicarious calibration can be tuned using match-up data from the MOBY site and/or cross calibration with another sensor. The SIMBIOS Project can thereby provide a completely independent assessment of instrument calibration and sensor-to-sensor relative calibration. The Project is also able to provide insight to the sensor team in understanding how differences in calibration techniques and atmospheric correction algorithms propagate through the processing to produce differences in the retrieved optical properties of the water.

In addition, the SIMBIOS Project can provide an independent assessment of the standard Level-2 products produced by a sensor team. Using the SeaWiFS Bio-optical Archive and Storage System (SeaBASS)[16], a growing database of *in situ* measurements to validate the satellite-retrieved water-leaving radiances and pigment concentrations, we can compare the standard Level-2 products from one sensor with products from SeaWiFS or another sensor.

Table 1

CURRENT SIMBIOS LEVEL -2 PROCESSING APPROACH
• Multi-sensor Level 1B to Level 2 software package • Software currently able to process MOS, SeaWiFS, OCTS and POLDER • With reprocessing #3 the software is the SeaWiFS production code (possible multiple code comparisons in future) • Identical atmospheric correction algorithm used for all sensors • Common ancillary data sources for all sensors and match-up analyses

2.2. Validation of bio-optical properties

Having a standard set of measurement protocols is indispensable in developing consistency across the variety of international satellite ocean color missions either recently launched or scheduled for launch in the next few years. In the U.S., for instance, ocean color validation support is derived from four separate funding programs, i.e., the SeaWiFS Project, Moderate Resolution Imaging Spectroradiometer (MODIS) validation program, the Earth Observing System (EOS) calibration and validation program, and the SIMBIOS Project[1,2].

While each mission has its own validation effort, the mission validation teams should not need to define separate validation measurement requirements. The SeaWiFS and SIMBIOS Project have allocated resources to describe and develop protocols, or scientific approaches in accordance with the goals of the Projects. These NASA TMs are intended to provide standards, which if followed carefully and documented appropriately, will assure that any particular set of optical measurements will be acceptable for ocean color sensor validation and algorithm development[17,18]. These protocols are guidelines and may be somewhat conservative. Continued development and refinement of these protocols help ensure coordination, collaboration, and communication between those involved.

The SIMBIOS Project has an extensive set of *in situ* data for match-up analysis from the SeaBASS database, which is presently comprised of data from over 250 cruises and includes 400,000 pigment records (Figure 4). The *in situ* data in SeaBASS include measurements of water-leaving radiance and other related optical and pigment measurements, from ships, moorings and drifters. Various methods are deployed to collect of SeaBASS data, including the use of subsurface and above-water measurement devices[17,19].

SeaBASS data are used by the SIMBIOS Project to validate SeaWiFS and other (OCTS, POLDER, etc.) postlaunch imagery and to develop new operational chlorophyll algorithms. The SIMBIOS L_{wn} and chlorophyll $\underline{a}$ matchup procedure and analysis are described in Bailey et al.[20]. Presently, SeaBASS data sets include data from calibration round robins, the SeaWiFS prelaunch calibration and characterization data and a large number of bio-optical data sets for product validation and algorithm development.

A redesign of the SeaBASS database[18] started in Fall 1999, and is expected to be operational in Summer 2000. Changes to the database include (1) an increase in the number of tables to improve data normalization and database performance, (2) a reconfiguration of the system to take advantage of multiple computer processors and increased physical storage space, (3) the generation of stored procedures and tables for internal SIMBIOS Project Office accounting activities, and (4) the ability to ingest bio-optical and pigment data into tables within the database. The latter will allow specific data values to be extracted by performing simple keyword searches on the metadata or by applying range conditions (e.g. waveband, depth, etc.) on the data tables. A current description of the SeaBASS system is available via the World Wide Web at http://seabass.gsfc.nasa.gov.

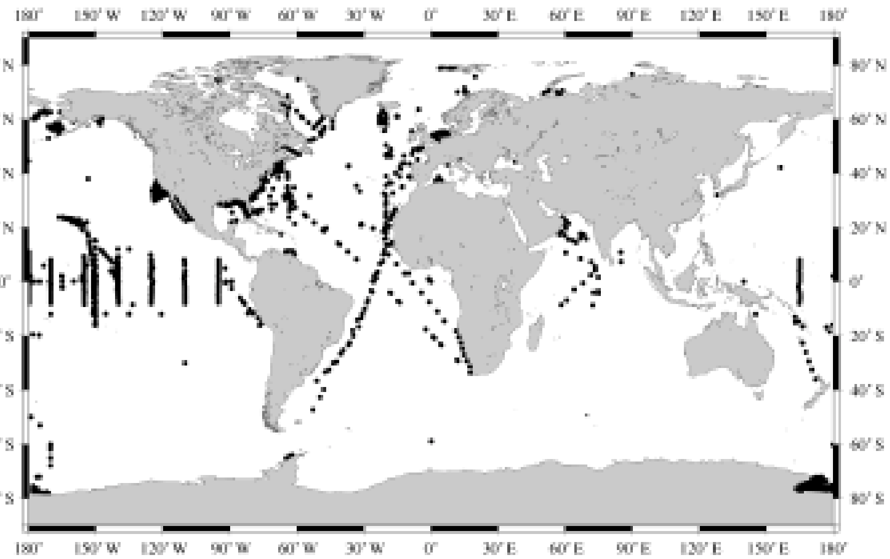

Figure 4. Bio-optical & atmospheric *in situ* data submitted to SeaBASS (1997-2000)

2.3. Validation of aerosol optical thickness

Imagery from different ocean color sensors with MS1l2 can be processed by a single software package using the same algorithms, and adjusted by different sensor spectral characteristics and the same ancillary meteorological and environmental data. This enables cross-comparison and validation of the data derived from satellite sensors and, consequently, creates the continuity of ocean color information in temporal and spatial scales. The next step is the integration of *in situ* obtained ocean and atmospheric parameters to enable cross-validation and further refinement of the ocean color methodology.

Atmospheric correction of satellite radiances and, in particular, estimation of aerosol effects on the upwelling radiance at the top of the atmosphere is one of the most difficult aspects of satellite remote sensing. Merging of aerosol properties obtained from *in situ* observations with those derived by sensor algorithms creates exceptional opportunities to validate and improve the atmospheric correction[18,21].

There are many uncertainties associated with *in situ* measurements themselves. They include sun photometer or radiometer calibration and operation problems, inadequate handling by people, and cloud contamination. When matching against atmospheric properties obtained by a satellite sensor, additional uncertainties come into play which are caused by different viewing angles by the satellite and the surface instrument and by time discrepancies when both media acquire their observations. In the case of atmospheric properties, these uncertainties may be considerable. Therefore, the fine calibration of sun photometers and radiometers is needed as well as the best possible and most uniform instrument to instrument measurement correction. Multiple observations from different sun photometers and radiometers requires cross-validation of the quality of *in situ* data, extraction of measurements with high stability and confidence, and comparison of these measurements against satellite sensor estimates with a larger degree of certainty.

Recently, the SIMBIOS Project has implemented its own correction strategy for converting instrument voltages to aerosol optical thickness (AOT). The approach ensures a uniform AOT processing for all instruments making the AOTs comparable for the SIMBIOS sun photometers[22,23], as well as between instruments and satellite sensor AOTs derived by means of the atmospheric correction. Also, the method uses a consistent set of tuning variables, such as ancillary data, concurrently applied for the correction of satellite radiances. Therefore, some stages of the satellite and *in situ* data processing are identical which beneficially contributes to confidence in the match-ups. For the aerosol measurement bands of satellite sensors that cannot be vicariously calibrated by other means[12], these AOT measurements provide a very good means for checking sensor performance.

The SIMBIOS Project has an atmospheric instrument pool consisting of 12 MicroTops hand-held sun photometers, 2 PREDE sun photometers (Japanese), 2 SIMBAD and 2 SIMBADA sun photometers developed by the Laboratoire d'Optique Atmospherique (LOA, France), 1 micro-pulse lidar, and an additional 12 "hardened" CE318 CIMEL instruments (Figure 5). After undergoing a robust re-engineering, the 12 hardened CIMEL instruments are designed to better withstand the corrosive marine environment, and now augment the AERONET[24] network with coastal and island stations.

Figure 5. SIMBIOS sun photometers

3. RESULTS

The overall objective of the data merger component is to develop and test methods of combining data from different merger sources to provide time series of global fields. Sources may have different inherent spatial and temporal resolutions and different methods may be required depending on the geophysical quantity, e.g., chlorophyll-a, water-leaving radiance, primary productivity, etc. Data merger algorithm development is the focus of two SIMBIOS science team investigations (e.g., NRA-99), both of which are in the design and evaluation phase.

The SIMBIOS Project uses vicarious test sites to compare ocean color satellite instruments. Several intercomparisons and cross-calibrations have been completed or are in progress. In the last year, SIMBIOS has successfully collaborated with several international groups, including OCTS (Japan), MOS (India and Germany) and POLDER (France). Data processing (Raw-0 to Level-2) software for OCTS, MOS and POLDER have been completed.

3.1. MOS

On February 1999 SIMBIOS Project began operating a receiving station at NASA's Wallop Flight Facility (WFF) to acquire data from MOS, a German instrument onboard the Indian IRS-P3 satellite. The data from WFF are processed at NASA's Goddard Space Flight Center (GSFC), with routine distribution of Level-0 data sets to the German Remote Sensing Data Centre (DLR-DFD). Data are freely available to the public in accordance with the data distribution policies of DLR-ISST (see MOS browse at http://seawifs.gsfc.nasa.gov /mos_scripts/mos_browse.pl)

SIMBIOS activity included evaluations of the navigation, calibration (detector-relative and absolute), atmospheric correction, and bio-optical algorithms[25,26]. For the intercalibration of SeaWiFS and the MOS, co-located measurements in the Adriatic and Mediterranean Seas and the Atlantic Ocean were used. Wang and Franz[26] demonstrate that it is possible and efficient to vicariously intercalibrate two different ocean color sensors. The MOS results are in reasonable agreement with SeaWiFS and spatial data merging techniques are presently being evaluated (Figure 6).

3.2. OCTS

From measurements of the MOBY buoy and from other sites by OCTS, vicarious calibration coefficients have been derived by the NASDA ocean color team and by the SIMBIOS Project[1,2]. Considering that the two projects use different atmospheric corrections[27] and different *in situ* measurements for calibration, the two sets of results are in very good agreement[2]. The largest difference is in the 765nm band, which NASDA does not use for atmospheric correction, but which SIMBIOS uses and corrects for oxygen absorption.

Match-up comparisons between field and OCTS data used subscenes provided by NASDA. Vicarious calibration of the OCTS was performed using *in situ* data from the MOBY buoy. Two validation analyses were performed: a comparison of OCTS data processed by SIMBIOS to in situ measurements obtained from the SeaBASS data set .

Furthermore, Gregg et al.[28] assessed geometric and radiometric performance of a limited set of OCTS data from the US East Coast and the Gulf of Mexico. Results indicated a geometric offset in the along-track direction of 4-5 pixels that was attributed to a tilt bias, but radiometric stability was inconclusive due to daily variability. Comparison with co-located *in situ* measurements showed that the pre-launch calibration required adjustment from -2% to +13%[28].

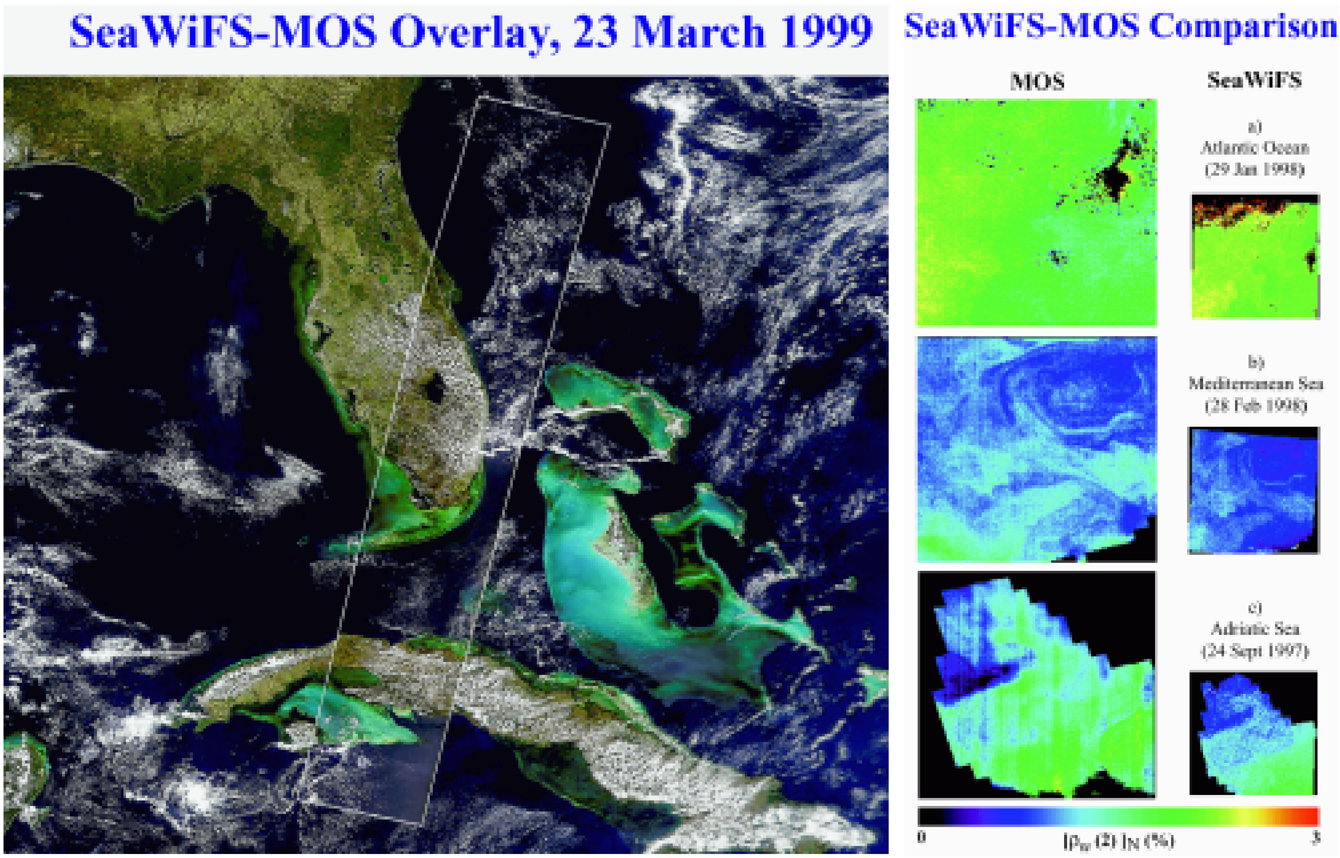

Figure 6. SeaWiFS and MOS scene merged (on the left); and SeaWiFS-MOS comparison in the Atlantic Ocean and Mediterranean Sea (on the right)

3.3. POLDER

During the Spring of 1999 the SIMBIOS Project began collaborations with scientists from CNES and the University of Lille, France. Using the same MOBY data set, CNES and SIMBIOS personnel performed a vicarious calibration of POLDER using CNES and SIMBIOS processing software, respectively, and achieved similar results. Joint papers are anticipated from this collaboration, and the SIMBIOS Project plans to implement POLDER processing within SeaDAS[29].

POLDER I and II have no onboard calibration system because of their original CCD matrix design. Hence efforts have been carried out to develop in-flight calibration algorithms using natural targets such as Rayleigh scattering, ocean sun glint or desert sites[30]. The cross-calibration of POLDER, OCTS and SeaWiFS level 1b products also been performed over desert sites[31], and the discrepancy observed at 443 nm between POLDER and SeaWiFS is confirmed by vicarious calibration. Vicarious calibration relies on *in-situ* measurements of both ocean and atmospheric conditions. It is different from the absolute calibration method mentioned above[30], which relies on *a-priori* time and spatial stability of specific ocean areas. For the POLDER ocean color measurements, some vicarious calibration measurements have been made using the SIMBAD instrument[32], and some large differences have been observed in the blue bands. Vicarious calibration coefficients have been chosen for the processing of level 2 POLDER ocean color products, and some new vicarious results using MOBY measurements have confirmed these coefficients. However, a slight difference of 1% for the 490 nm channel has been detected. New level 2 POLDER ocean color products are currently being processed at CNES with the new 490 nm calibration coefficient.

Comparisons of POLDER and SeaWiFS level 2 and level 3 have been made on a global scale showing good agreements for the ocean surface reflectance at 443 nm but some discrepancies occur for the 490 and 565 nm channels at high latitudes. Some improvements on the multiangular POLDER calibration algorithm in the near future should help to understand these differences.

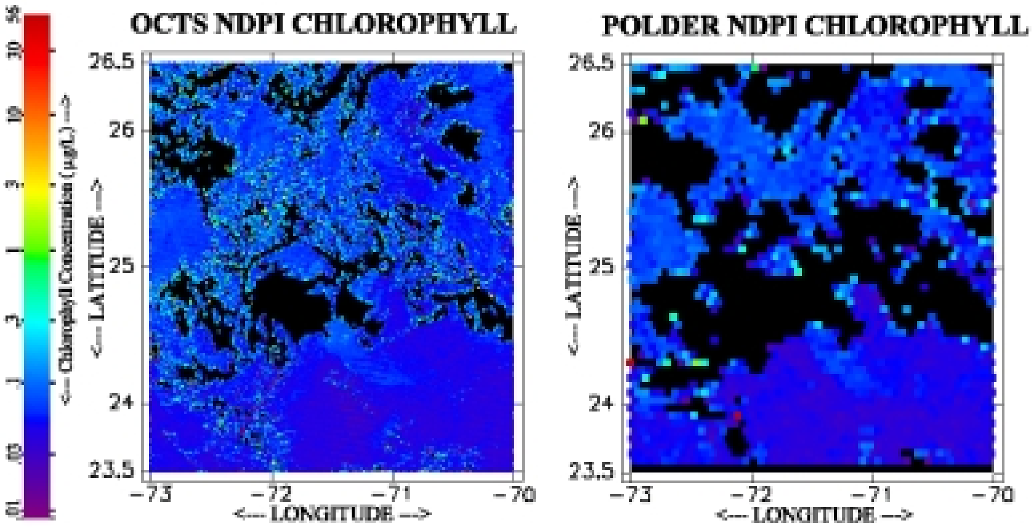

Figure 7. A scene from January 29, 1997 in the Sargasso Sea as seen by the OCTS and POLDER. Level 1 data from both instruments were processed to Level 2 by the SIMBIOS Project and NDPI pigment computed, then converted to NDPI chlorophyll. 27 such scenes will be used to compare similarities and differences between the two instruments

In an attempt to directly compare the POLDER and OCTS instruments, the SIMBIOS Project has mounted an effort to process both OCTS Level 1b or Level 0 and POLDER Level 1b ocean color data using SIMBIOS processing methods. Since POLDER and OCTS both flew aboard the ADEOS-I satellite, their data are temporally coincident although their spatial resolutions are different (Figure 7).

CNES has supplied the SIMBIOS Project with both Level 1 and Level 2 data sets encompassing the dates and locations used for the projects OCTS studies. The vicarious calibration of POLDER was performed using MOBY matchups and procedures similar to those used to calibrate the OCTS for SIMBIOS processing, and the POLDER Level 1b data were processed to Level 2 and run through the matchup analysis procedure. The complete set of matchups of SIMBIOS-processed Level 2 to SeaBASS *in situ* data is finished and results may be seen at http://simbios.gsfc.nasa.gov/~alice/polder_matches/INDEX.html. Large-scale statistics of the POLDER Sargasso Sea data have been generated and a meaningful comparison of the OCTS and POLDER is underway using these results. This comparison will identify both consistent similarities and differences between the instruments.

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